# Evidence for aeolian origins of *heuweltjies* from buried gravel layers

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Although *heuweltjies* (19–32 m diameter) dominate the surface of much of the southwestern Cape of South Africa, their origins, distribution and age remain controversial. Current hypotheses are that the *heuweltjies* are (1) constructed by the excavation and mounding habits of burrowing animals; (2) the result of erosion by water of areas between patches protected from fluvial action by denser vegetation or (3) the product of localised aeolian sediment accumulation beneath denser vegetation associated with termitaria. At a site where quartz-containing gravels occur on the soil surface in areas between *heuweltjies*, these gravels were found to extend as a relatively intact layer of uniform concentration from the inter-mound area into the mound at the same plane as the surrounding soil surface. This buried layer suggests that *heuweltjies* were either built-up by deposition on a previous soil surface layer or eroded from sediment accumulated above the buried gravel layer. Mounds contain a relatively large proportion of silt consistent with sediment deposition. Mound sediment elemental composition was strongly correlated with that of local shale, indicating a local source of sediment. Pedogenesis was considerably more advanced off- than on-mound. There was no evidence of extensive regional aeolian sediment mantling over the vast area in which the *heuweltjies* occur. These findings and observations support the aeolian deposition hypothesis of *heuweltjie* origins combined with a degree of erosion, rather than a termite bioturbation hypothesis or a predominantly erosion-based hypothesis.

## Introduction

To date three classes of hypotheses have been invoked to explain the regular (i.e. over-dispersed) patterning and the raised circular forms of *heuweltjies,* mounds of about 20 m in diameter that occupy 1.2% of the southwestern Cape landscape.[1] The *bioturbation hypothesis* suggested that they were constructed by earth-moving activities of fossorial mammals and/or termites,[2–4] although the role of mammals has largely been considered to be secondary to termites.[4] Inter-mound distances are considered to be within a range that competing aggressive termites may realistically space themselves.[4] Cramer et al.[5] argued that mounds are far too large to have been made by any known termite. Instead of *heuweltjies* being constructional features, they argued that erosion by water of areas not protected by regularly spaced vegetation clumps is the mechanism responsible for the mounds and their spacing, similar to mounds in Brazil.[6] McAuliffe et al.[7] rejected this *erosion hypothesis* and suggested an *aeolian accretion hypothesis* in which aeolian sediment has accumulated around regularly spaced loci, similar to the formation of coppice dunes (also known as nebkhas or nabkhas).[8] McAuliffe et al.[7] argued that harvester termite mounds initiated the regular vegetation patterning by providing nutrient-rich soil loci for plants. Termites are also thought to have provided a local accumulation of calcium oxalate-rich plant biomass, which has facilitated the development of the calcified layer characteristic of many *heuweltjies*.[2,4, 7–11]

McAuliffe et al.[7] studied *heuweltjies* on the low-relief plain near the west coast of South Africa with widespread aeolian sand deposits. This voluminous sand supply was implicated as the sediment source for the rather large (about 30 m diameter, 2 m height) *heuweltjies* that commonly occur in that area. These authors used the greater degree of pedological development of off-mound soils to argue for aeolian deposition of sediments on mounds than intervening areas. Despite some differences in on- and off-mound sediment particle sizes,[7] the particle size distributions are broadly similar,[3] suggesting that the sediments on- and off-mounds were originally derived from the same source.

In addition to textural differences between on- and off-mound soils, there are also chemical differences that relate to the process that lead to mound formation. It has been commonly observed that *heuweltjies* have petrocalcic (i.e. calcrete) horizons that are absent in the off-mound areas.[11] McAuliffe et al.[7] concluded that the variability in the development of petrocalcic horizons may be associated with the age of the mounds, with older *heuweltjies* forming more extensive petrocalcic horizons. *Heuweltjie* calcretes are ancient[11] and the source of their Ca is contentious. McAuliffe et al.[7] and others have suggested that source of the Ca was the termites *Microhodotermes viator*, that have been proposed to partially forage off-mound and deposit Ca-rich frass on-mound.[7,11,12] *Heuweltjie* soils also contain higher concentrations of N, P, K, B, Cu, Fe, Mn and Zn,[13,14] and bioaccumulation by termites has also been invoked to explain the accumulation of these other nutrients.[7] Based on $^{87}Sr/^{86}Sr$ ratios of calcrete that are distinct from underlying rocks, it has, however, been suggested that the source is of marine origin delivered via atmospheric transport.[12] Finally, Ca accumulation on-mound was also suggested to be the consequence of plant nutrient mass-flow concentrating nutrients around plant roots,[5] analogous to the formation of caliche associated with 'islands of fertility'.[15,16] Clearly, the formation of *heuweltjies* and associated calcrete and nutrient-rich soils continues to be contentious.

Identifying previous soil surface levels would provide a test of all three hypotheses above. The *aeolian deposition hypothesis* would predict that surface gravels, indicative of the level of a previous soil surface within a mound, should largely be on the same level as those off-mound. This would indicate that the mound has been constructed on top of a previous soil surface. In contrast, the *bioturbation hypothesis* suggests that termites capable of moving particles less than 1 mm in diameter[17] would cause coarse surface gravels in mounds to sink below those in the off-mound soil.[1] This would occur as termites gradually excavate their subterranean tunnels and storage sites

and as they carry finer soil particles upwards to construct their indurate mounds. Some of these gravels may later be returned to the surface through mammalian bioturbation, for instance by moles, porcupines and aardvarks. If prior to mound formation the land surface contained distributed gravel, the *erosion hypothesis* would predict that surface gravel off-mound would be lower than that within the mound, as off-mound erosion would cause them to sink relative to those protected from erosion within the mound.

We selected a study site in the southwestern Cape in South Africa at which a continuous gravel layer exists in the off-mound surface layer. Relative to the age of *heuweltjies*, this layer may be ancient, as evidenced by associated endemic dwarf succulent plant species and specific plant communities.[18] Also, this layer was found within *heuweltjies* indicating it predates the formation of *heuweltjies* (This gravel layer will be discussed later in the article). We used this gravel layer to test the above three hypotheses, and also used particle size and elemental analysis to provide additional information to substantiate our conclusion that vegetation accelerated aeolian deposition likely accounts for mound formation.

## Methods and Materials

### Study site

We sampled mounds near Worcester (33° 37.416S, 19° 32.226E) in vegetation identified as Robertson Karoo. This site is underlain by Bokkeveld Group metasediments, including shale and quartz veins. The *heuweltjies* that were sampled are situated on the concave lower slopes of a hill (240 m above study site). The site has a mean annual temperature of 16.7 °C and 455 mm annual precipitation, 205 mm of which falls in the coldest quarter and 43 mm in the warmest quarter (http://www.worldclim.org/bioclim). The vegetation of the region is low stature (<2 m) and shrubby with many succulents occurring on the mounds. The mound boundaries were readily identifiable by the change in vegetation, with important on-mound genera being *Aloe*, *Euphorbia*, *Cotyledon*, *Tylecodon*, *Searsia* and *Euclea*. The study site was selected because it has gravel on the inter-mound surface (Figure 1a). This gravel layer consists predominantly of quartz, but shale fragments are also present. Quartz veins are evident in the landscape immediately upslope of the *heuweltjies*. Although some *heuweltjies* at the locale contain well-developed layers of calcrete within them, several of the mounds examined in this investigation lacked such layers (Figure 1b).



**Figure 1:** (a) A shallow pit off-mound with surface gravel including quartz that was used to indicate whether the mound was the product of erosion or accretion; (b) a soil pit in a mound with coarse gravel exposed in a side wall and a gravel accumulation visible above an indurate duripan at the base of the pit.

### Mound survey

Seven mounds were selected on terrain with a moderate slope (<10%). For each mound, the perimeter of the mound was defined on the basis of the change in elevation and vegetation characteristics. The down-slope and across-slope directions were determined and then a Leica NA720 Automatic Level (Leica Geosystems, Johannesburg, South Africa) was used to measure the elevation of the mounds at about 1 m intervals starting from 2 m into the off-mound area downslope and continuing across the mound to 2 m off-mound upslope. The measurements were used to calculate the maximum height of the mound above a linear interpolation between the off-mound points in two orthogonal directions, and these heights were averaged. This allowed estimation of the depth the gravel layer would be expected within the mound. The mound diameter was used to estimate the mound area for the approximately circular mounds. The mound volume was estimated from the area and the average heights of the mounds in the two measured orthogonal directions.

### Gravel, soil and rock sampling

Sampling was carried out from the surface off- and on-mound to the depth of a hard, gravelly duripan. In the case of the biggest mound, this duripan coincided with a strongly cemented petrocalcic horizon. Initial sampling (*n*=7) of mounds was conducted using a 0.07 m diameter auger allowing sampling in 0.22 m increments and ready identification of the location of the gravel layer. Considering the difficulty of getting the auger through the duripan horizons below the gravel layer, we also excavated pits in a subset of mounds (*n*=5). In addition to these mounds, one of the largest mounds in the area was also excavated. For pits, the soil area was marked out in a 0.2 m x 0.2 m area and excavated in 0.2 m intervals. Off-mound sampling was restricted to a single 0–0.2 m depth, but on-mound sampling was to a maximum depth of 0.8 m, apart from the large mound that was sampled to a depth of 1.8 m. The soil excavated by auger or from each 0.2 m x 0.2 m volume was sieved through a 0.005 m mesh sieve. Care was taken to break up peds so that only coarse gravel remained on the sieve. The coarse gravel and sieved soil were transported to the laboratory and the stones were weighed. The sieved stones were subject to size fractionation using a test sieve shaker (Endecott Ltd, London, UK) and then each fraction was weighed. We were able to get a larger and more representative sample from the pits than from using the auger, so we based measures of gravel concentration, particle size and pH on samples from the pits. The 5 mm sieved soil was air-dried for 48 h and then 1 mm sieved samples were split by repeatedly quartering the soil and taking opposite quarters for each successive sub-sample to provide samples of appropriate volume[19] for particle size analysis and elemental analysis. Samples of shale and quartz from rock outcrops were collected, the surface cleaned with a steel brush followed by washing with a domestic power washer before being crushed.

### Soil particle size analysis

Soil particle size distributions were analysed using a Malvern Mastersizer 2000 (Malvern Instruments Ltd, Malvern, UK) on sieved soils smaller than 1 mm suspended in water and ultrasonically dispersed, stirred and introduced to the laser diffractometer with a Malvern Hydro 2000G wet dispersion unit. The organic material that floated to the surface was removed by hand. Each sample was subjected to 180 s ultrasonic dispersal to ensure complete disaggregation of particles. The proportion of the soil particles in each size class were recorded and plotted. These size classes were then summed into categories representing clay, silt and sand, according to the Wentworth grain size chart.[20]

### Soil and rock elemental and pH analysis

Sieved (<1 mm) soil and crushed rock samples were milled to a fine powder with a mortar and pestle. The powder was placed in sample cups with a polypropylene bottom and analysed in a Spectroscout energy-dispersive X-ray Fluorescence (XRF) analyser (SPECTRO Analytical Instruments, Kleve, Germany). The duration of sampling for each filter was set to 100 s for each of the Pd, Mo and Ta filters and 100 s without a filter. The instrument was calibrated by using a certified standard GBW07312 (National Research Center for CRMs, Beijing, China), for which elemental concentrations were obtained from NOAA Technical memorandum NOS ORCA 68 (1992). The elements measured (all above detection limit in all samples) were Na, Mg, Al, P, K, Ca, Ti, V, Cr, Mn,

Fe, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Ba, W, Hg, Tl, Pb, Bi and Th. Soil pH was measured by suspending about 20 g sieved air-dried soil in 50 mL 1 M KCl, stirring with a glass rod, allowing to settle for 1 h and then immersing a pH electrode in the supernatant.

### Mound profile descriptions

Profile descriptions were made in two on- and one off-mound position. Major horizons were identified, measured and sampled (multiple samples were taken in thick horizons). The profiles were excavated to the depth of the impenetrable duripan for one mound and the nearby off-mound sites. For one larger mound, sampling was carried out to a depth of 1.8 m, where a nodular calcrete layer prevented further excavation. Sampling to this depth was only possible because of prior excavation by an aardvark, which had dug through an indurated layer, which appeared to be a combination of duripan and calcrete. These samples were analysed for particle size and XRF elemental analysis was conducted as described above. The presence of carbonates was also confirmed by testing the effervescence with the addition of a 10% (v/v) HCl solution. Soil horizon characteristics were described following guidelines for soil description (FAO).[21]

### Statistical analyses

Soil gravel concentration, soil pH and elemental concentrations were analysed using ANOVA with post-hoc Tukey tests and general linear models in R[22] to determine whether there were significant ($p<0.05$) differences between the values. Linear regression and confidence intervals were calculated using *ggplot2* in R.

## Results

### Mound morphology and profiles

The surveyed mounds had small volumes relative to other mounds in the region (c.f. Cramer et al.[5]) and an average height of only 0.32 m above the landscape surface (Table 1), apart from the one larger mound sampled, which had a height of 1.1 m. Nevertheless, the mounds were clearly demarcated by changes in vegetation and elevation[23] and characterised by a dramatic decrease in the amount of gravel on the soil surface. Excavation by auger revealed that there was a concentration of gravel at 0.48 m below the mound surface on average (Table 1), but

considering the difficulty penetrating below this gravel layer with an auger, we also opened soil pits. In the subset of mounds ($n=5$) in which pits were excavated, the depth at which the maximum concentration of gravel was found with the auger ($0.54\pm0.06$ m) was slightly shallower than from pits ($0.61\pm0.07$ m), but this difference was not significant (Student's paired sample *t*-test, $p=0.121$). The difference between the depth at which the gravel layer was found and the expected depth of this layer, based on the maximum mound heights, was not significant (Student's *t*-test, $p=0.076$). Mound heights and the depth to the duripan layer were also significantly correlated with the depth at which the gravel layer was found (Figure 2).

**Table 1:** Characteristics of mounds excavated with an auger for which morphological properties were measured ($n=7$).

| Mound characteristic | Unit | Mean ± SE |
|---|---|---|
| Maximum landscape slope | % | 9.0 ± 0.6 |
| Area | m² | 551 ± 82 |
| Volume | m³ | 140 ± 41 |
| Maximum mound height above landscape | m | 0.32 ± 0.05 |
| Depth excavated | m | 0.57 ± 0.08 |
| Depth of gravel layer | m | 0.48 ± 0.06 |
| Expected depth of gravel layer | m | 0.42 ± 0.05 |

In the inter-mound area, the surface gravel was relatively uniformly exposed, or buried below small accumulations of sediment around vegetation (Figure 1a). The off-mound gravel proportions per size class were 0%>31.5 mm, 23%>16 mm, 61%>8 mm and 15%>5 mm, and the on-mound gravel (averaged over all depths) comprised 9%>31.5 mm, 21%>16 mm, 54%>8 mm, 16%>5 mm. The gravel was mainly quartz with some shale fragments. In contrast, the density of gravels on the mound surfaces was much lower, although some gravel was still present throughout the profile. At the depth of the
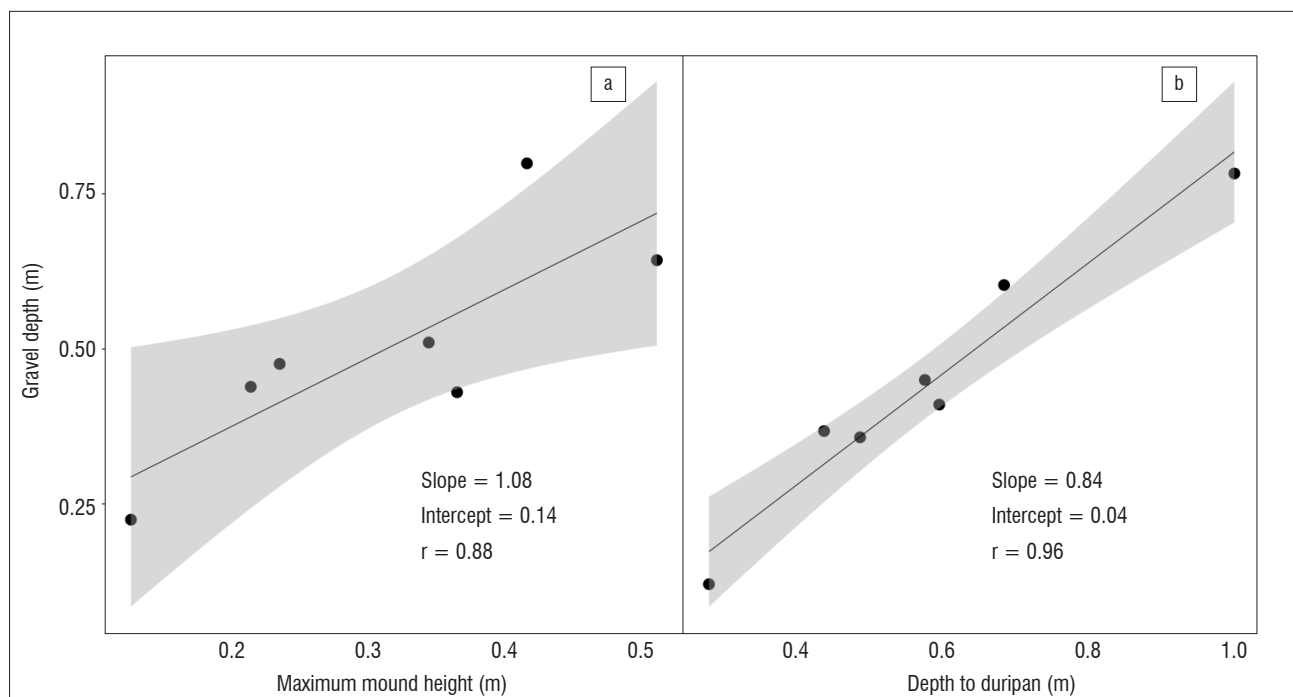


**Figure 2:** The depth below the mound surface of the maximum accumulation of gravel within each mound (assessed with an auger) was linearly related ($p<0.01$) to the maximum height of the mounds above the surrounding landscape and to the depth to the duripan layer ($n=7$). The grey band indicates the 95% confidence interval. The slopes, intercepts and Pearson correlation coefficients are shown.

maximum accumulation of gravel within the mound, the average gravel concentration was similar on average to that off-mound, although the variance was high between mounds (Table 2).

The soil profile (Figure 3) confirmed the presence of a concentrated gravel layer situated on top of an impenetrable duripan layer both on- and off-mound. From a sample taken using a hammer and chisel, this gravel continued into the duripan layer. The profile for this mound showed a significant reduction in gravel in the horizons above this concentrated gravel layer. This mound profile has a horizon that is only moderately calcareous, with no petrocalcic horizons present in the profile. The off-mound profile also has an increased concentration of gravel above an impenetrable duripan layer. Upwards, this gravel concentration first decreases and then increases again towards the surface.

**Table 2:** The variation in the concentration of gravel (kg/m³) with elevation in the soil profile above the duripan layer of excavated mounds and corresponding off-mound areas ($n=5$). The cumulative concentration of gravel on-mound is shown for comparison with the off-mound gravel, and the concentrations have also been averaged across mounds. Two of the mounds excavated were less than 0.6 m above the duripan layer in height.

| | | Mound | | | | | |
|---|---|---|---|---|---|---|---|
| Position | Elevation | 1 | 2 | 3 | 4 | 5 | Average |
| Off-mound | Duripan – 0.2 m | 575 | 430 | 658 | 869 | 210 | 548 |
| On-mound | 0.6–0.8 m | 2 | 27 | | | 18 | 16 |
| | 0.4–0.6 m | 1 | 42 | 48 | 139 | 27 | 51 |
| | 0.2–0.4 m | 47 | 612 | 177 | 63 | 22 | 184 |
| | Duripan – 0.2 m | 161 | 140 | 942 | 351 | 236 | 366 |
| | Cumulative | 211 | 821 | 1167 | 553 | 303 | 611 |
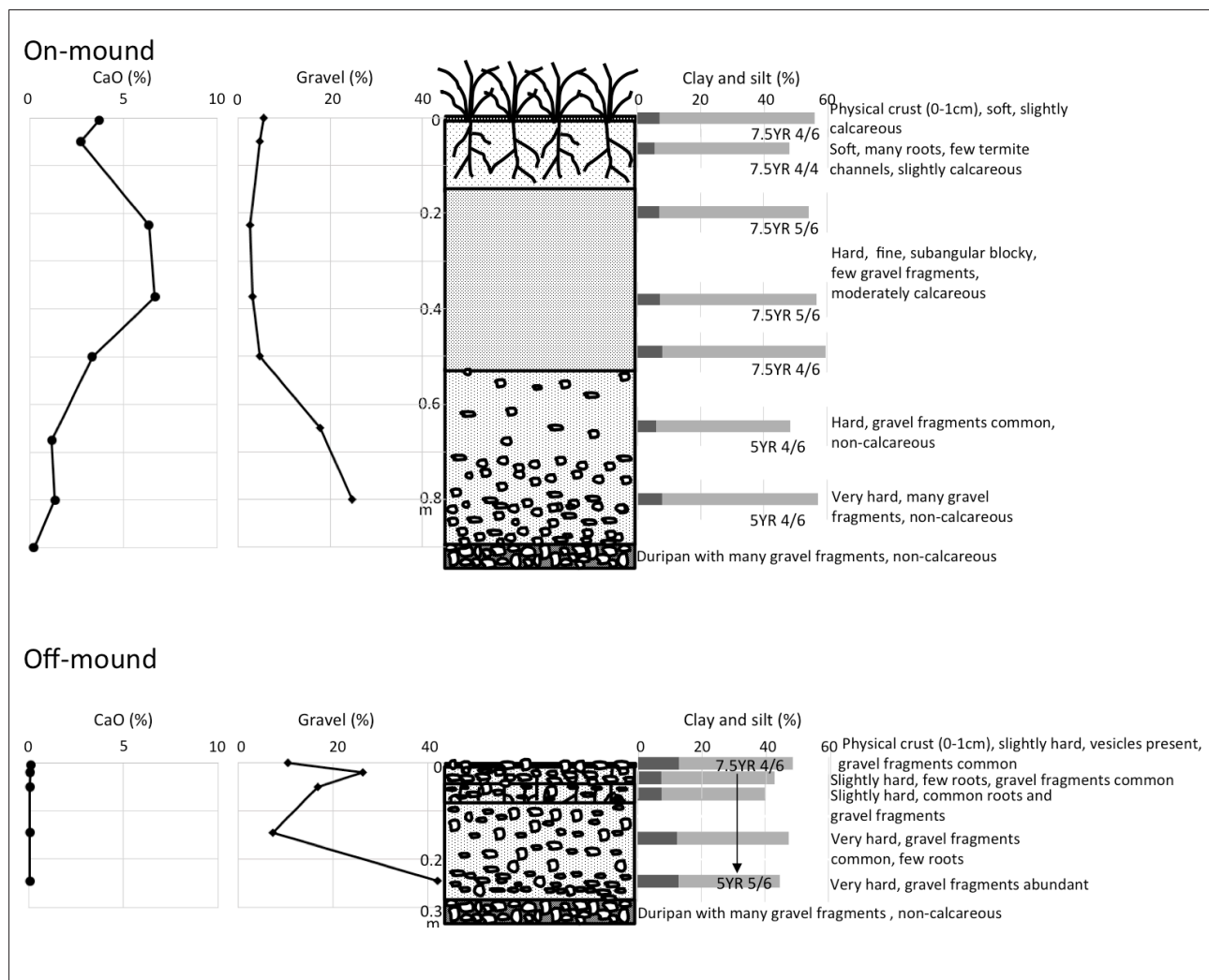


**Figure 3:** On- and off-mound profiles with CaO (%) of fines, proportion of gravel (% by mass) and proportion of clay and silt of < 1 mm fraction (% by volume). Horizon boundaries are gradual in most instances, but are illustrated here as abrupt for clarity. Gravel fragments and roots are not drawn to scale.

In the large mound for which a profile was described (Figure 4), gravel-sized fragments within a matrix of fines did not occur throughout the profile, although fragments of carbonate nodules did. The diagenetic carbonate accumulations and well-developed petrocalcic horizon occurred at 0.95 m depth and was associated with a duripan layer. This petrocalcic horizon varied from solid calcrete to accumulations of duripan containing no carbonate but also quartz gravel fragments. Below this calcrete is a layer of sub-rounded and angular carbonate nodules ranging in size from pebbles to larger cobbles[20] in a matrix of fines. This nodular carbonate accumulation becomes very dense and excavations were stopped at 1.8 m where it became difficult to penetrate any deeper.

### Soil particle size

Both on- and off-mound soils can be classified as poorly sorted, fine sandy loam at all sampled depths.[24] The lack of sorting is also evident from the particle size distributions (Figure 5), where the off-mound and deepest on-mound horizon (0.6-0.8m) show a clear bimodal distribution. The off-mound soils (0-0.2 m deep) had more sand and correspondingly less silt than the mound soils (Figure 5). The proportions of clay, silt and sand were respectively 7%, 36% and 57% off-mound, and 10%, 50% and 40%, respectively, on-mound (averaged across profile) with silt and sand differing significantly between on- and off-mound ($p=0.01$), but not clay ($p=0.07$). The proportions of clay and silt were greatest closest to the duripan layer within the mounds. The surface mound soil had more very fine and fine sand than the soil from deeper in the mound.

The off-mound profile particle size shows a variation from higher clay content on the surface, decreasing below this and then increasing again towards the duripan (Figure 3). The increased clay content on the surface is because of the vesicular, physical crusting present in the first 0–0.01 m as a result of fluvial deposition of fine material. The average
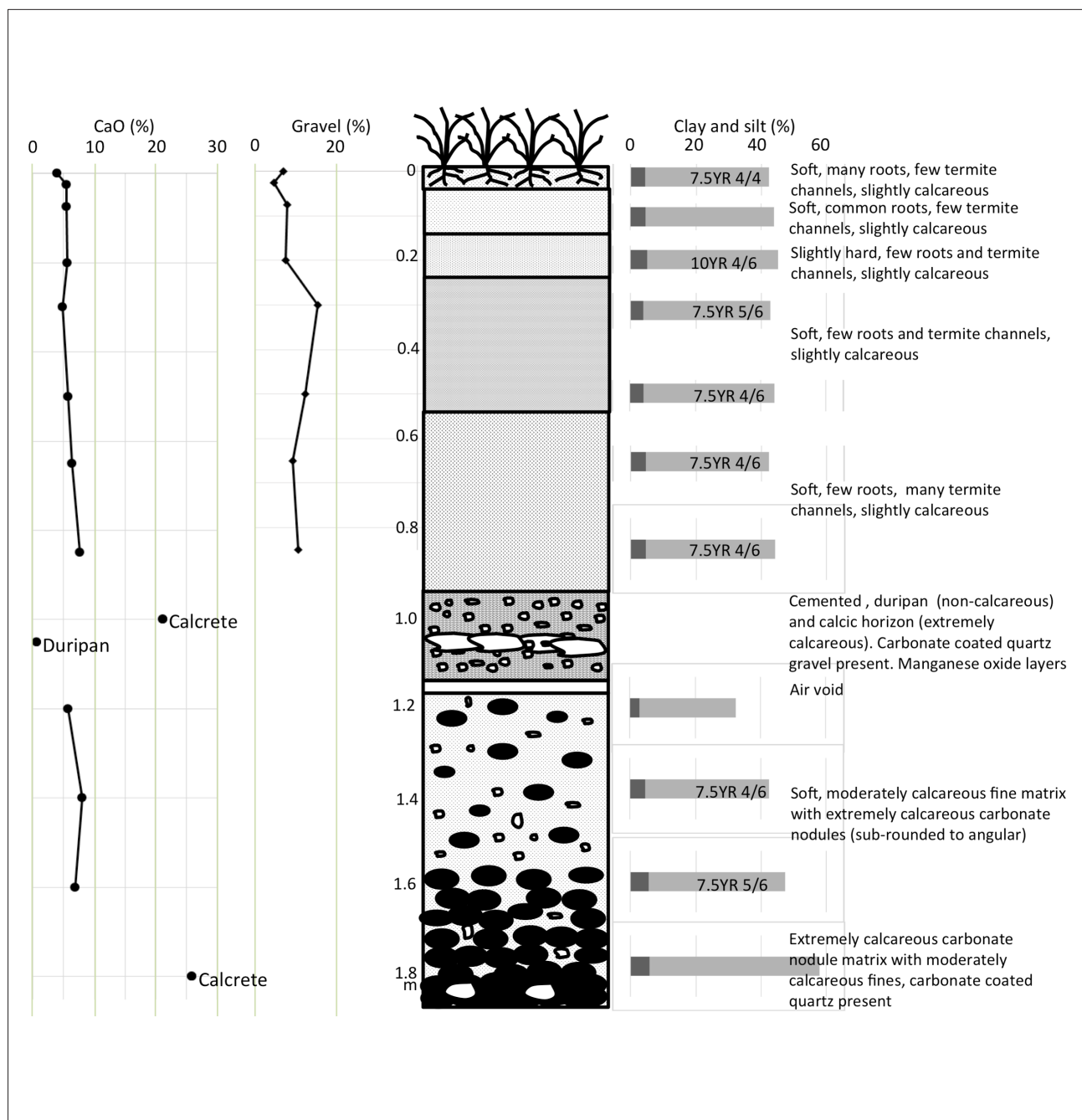


**Figure 4:** Profile of a large mound with calcrete. CaO (%) of fines is indicated as joined dots and CaO (%) of solid fragments as individual dots. Percentage gravel (% by mass) and proportion of clay and silt of <1 mm fraction (% by volume). Horizon boundaries are gradual in most instances, but illustrated here as abrupt for clarity. Gravel fragments and roots are not drawn to scale.

off-mound particle size distribution (Figure 5) shows a large variation in values for the silt and clay particle range.
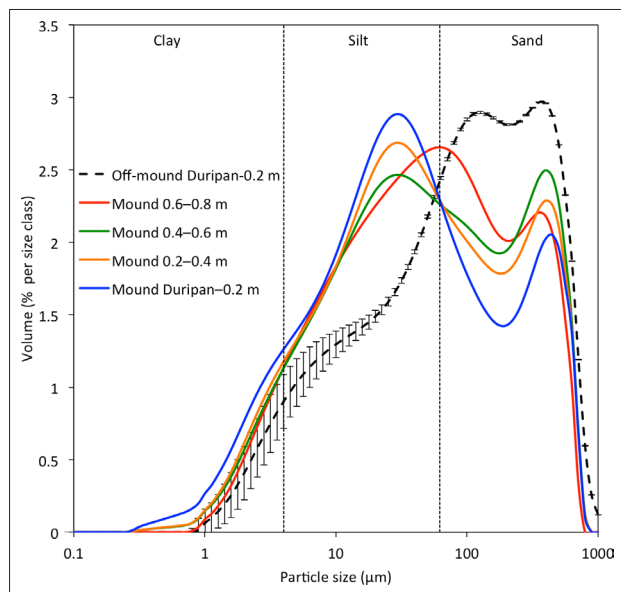


**Figure 5:** The variation in soil particle size between sieved (<1 mm) soil from on- and off-mound sites and with elevation above the duripan layer within mounds. The values represent the average for each particle size fraction ($n=5$). The error bars for the off-mound soil represent standard error. Error bars were not shown for the on-mound for visual clarity.

### Soil and rock chemistry

Soil pH was lower off-mound than on-mound and a linear model for pH with depth revealed a significant ($p=0.015$) increase in pH with elevation above the duripan layer on-mound (Figure 6, Table 3). Concentrations of P, K, Ca, Fe, Al and Rb were significantly higher and Na and Zr lower on-mound than off-mound (Figure 6). There were significant increases in P and Ca and decreases in K with elevation above the duripan layer on-mound. Off-mound soil elemental composition was strongly correlated with shale composition (Figure 7), but less strongly related to quartz (i.e. slope=0.89, intercept=0.53, $r=0.87$). Concentrations of Br, Zr and Ti were higher and Na and K lower than the 95% confidence interval on the regression of off-mound soil relative to shale. The elemental composition of on-mound soil (averaged across all depths) was less strongly correlated with shale composition than for off-mound soils (Figure 7). Concentrations of Ca, Br, Zr, Mn and Ti were higher and Na and K lower than the 95% confidence interval in the regression of on-mound soil relative to shale.

## Discussion

We found that all mounds comprised largely fine soils and little gravel with the gravel layer at the same plane as that off-mound. The degree of pedogenesis was greater off- than on-mound, consistent with McAuliffe's[7] findings. Together these observations support the hypothesis that the mound sediments are of aeolian origin, deposited over an existing gravel layer, rather than eroded from a former gravel-containing land-surface. Although traces of termites were found in the mounds, if they had played an important role in *heuweltjie* formation, we would have expected within mound gravels to be substantially lower in elevation than those off-mound.[2] The relative absence of gravel in the upper layers of the mound sediments is also unlikely to be the result of extensive termite bioturbational lowering of gravels, because the gravel layer lower down
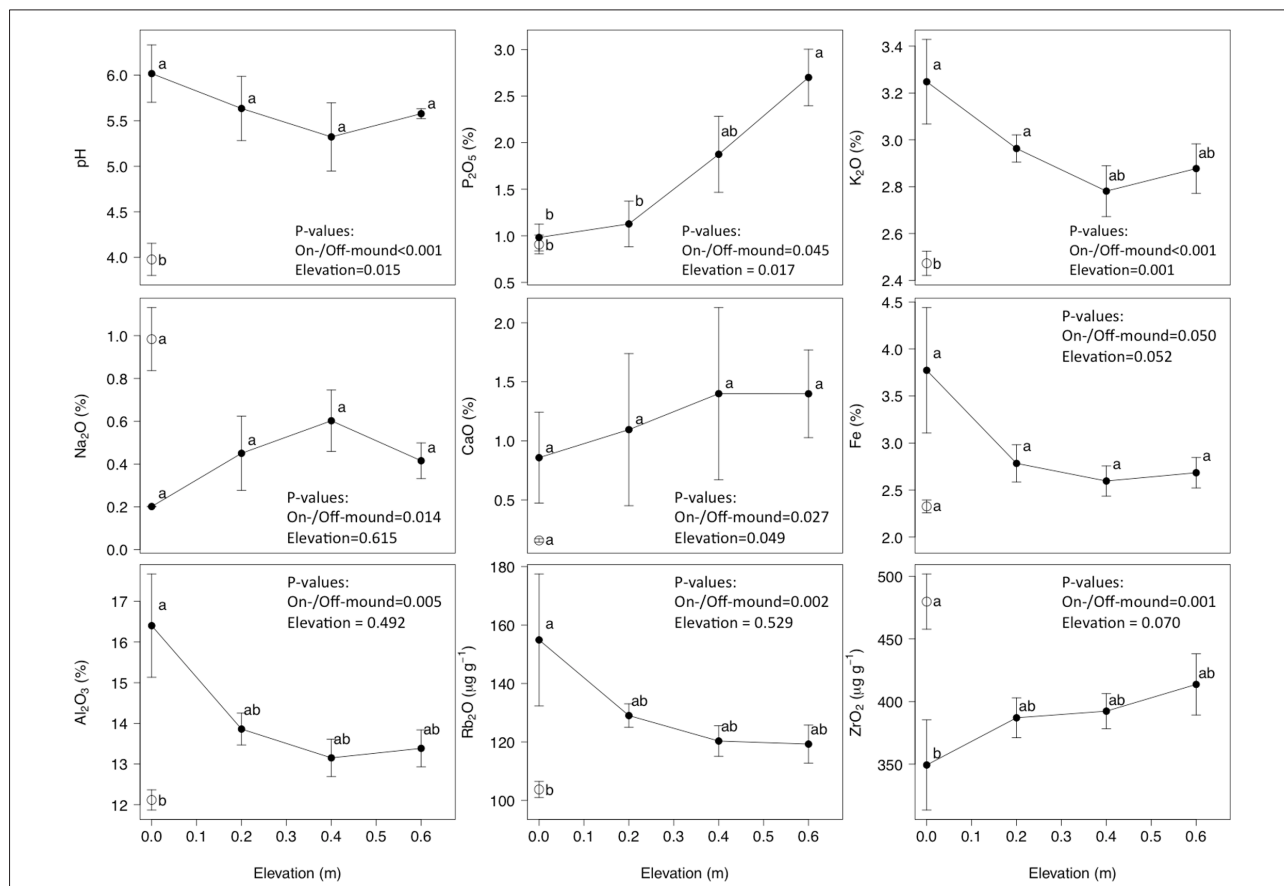


**Figure 6:.** The variation of soil pH and elemental concentrations between the on- and off-mound sites and with elevation in the mound profile above the duripan layer. The error bars indicate the standard error ($n=5$) and different letters indicate significant ($p<0.05$) differences as determined by ANOVA followed by post-hoc Tukey tests. The $p$-values in each panel are for the general linear model in which site (on- or off-mound) was a categorical predictor and elevation within mound a continuous predictor.
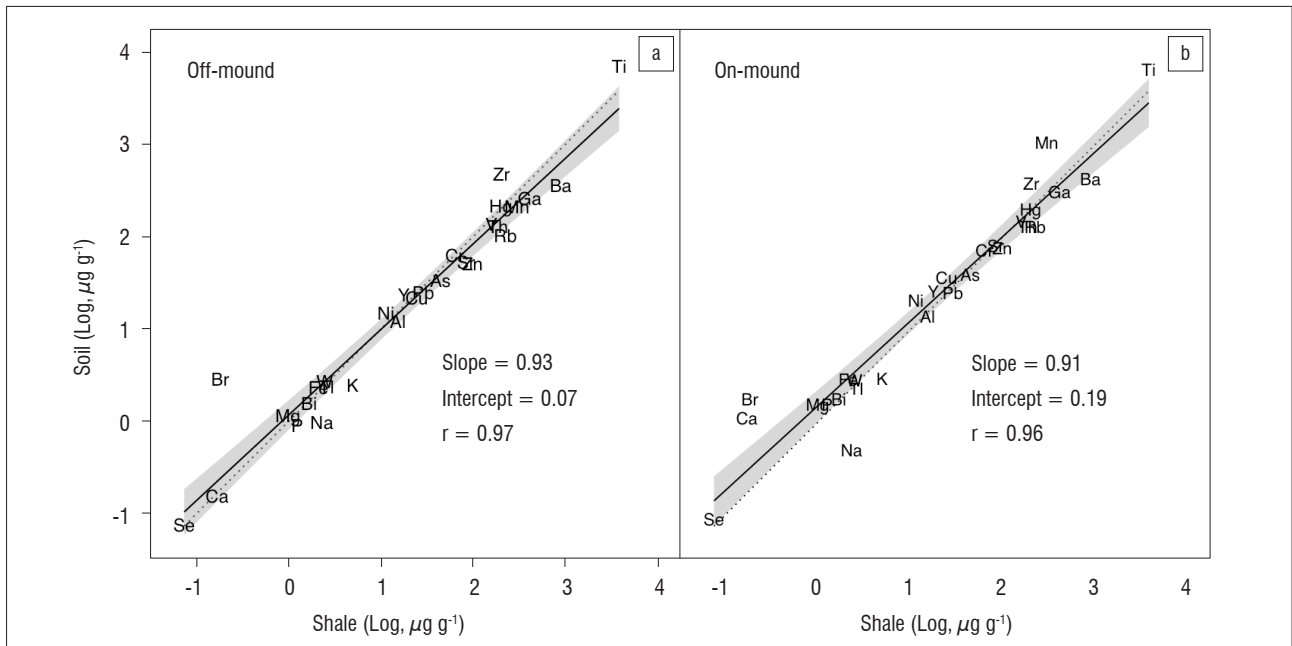
**Figure 7:** The correlation between the shale elemental composition and the elemental composition of on- and off-mound soil. The grey band indicates the 95% confidence interval. The slope, intercept and Pearson correlation coefficient are shown. The element positions are identified by their symbols and include Na, Mg, Al, P, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Ba, W, Hg, Tl, Pb, Bi and Th.

**Table 3:** The elemental concentrations of the off- and on-mound soils (averaged across all depths) with shale and quartz rock collected from the study site. The values are the mean ± SE.

| Element | Unit | Off-mound (*n* = 5) | On-mound (*n* = 5) | Shale (*n* = 3) | Quartz (*n* = 3) |
|---|---|---|---|---|---|
| $Na_2O$ | % | 0.98 ± 0.15 | 0.48 ± 0.05 | 2.29 ± 1.18 | 0.62 ± 0.05 |
| MgO | % | 1.16 ± 0.04 | 1.56 ± 0.04 | 0.98 ± 0.21 | 0.26 ± 0.04 |
| $Al_2O_3$ | % | 12.12 ± 0.25 | 14.24 ± 0.7 | 15.33 ± 0.66 | 2.57 ± 0.02 |
| $P_2O_5$ | % | 0.91 ± 0.1 | 1.47 ± 0.26 | 1.24 ± 0.37 | 4.24 ± 4.16 |
| K2O | % | 2.47 ± 0.05 | 2.97 ± 0.1 | 4.92 ± 0.64 | 0.71 ± 0.05 |
| CaO | % | 0.16 ± 0.01 | 1.06 ± 0.13 | 0.17 ± 0.04 | 0.22 ± 0.1 |
| $TiO_2$ | $\mu$g/g | 7048 ± 242 | 6487 ± 264 | 3858 ± 576 | 1167 ± 167 |
| $V_2O_5$ | $\mu$g/g | 138 ± 4 | 148 ± 1 | 160 ± 17 | 69 ± 13 |
| $Cr_2O_3$ | $\mu$g/g | 64 ± 3 | 72 ± 1 | 64 ± 17 | 33 ± 2 |
| MnO | $\mu$g/g | 215 ± 4 | 1031 ± 109 | 301 ± 19 | 91 ± 11 |
| Fe | $\mu$g/g | 2.3 ± 0.1 | 2.9 ± 0.2 | 2.1 ± 0.2 | 0.4 ± 0.1 |
| CoO | $\mu$g/g | 8.7 ± 0.2 | 9.9 ± 0.4 | 8.4 ± 0.3 | 3.6 ± 0.2 |
| NiO | $\mu$g/g | 14.9 ± 0.5 | 21 ± 0.7 | 11.4 ± 0.7 | 4.4 ± 0.7 |
| CuO | $\mu$g/g | 21.8 ± 1.8 | 37.5 ± 2 | 24.6 ± 8.5 | 6 ± 1.4 |
| ZnO | $\mu$g/g | 51 ± 0 | 77 ± 2 | 99 ± 18 | 158 ± 28 |
| Ga | $\mu$g/g | 265 ± 8 | 318 ± 20 | 414 ± 35 | 114 ± 17 |
| $As_2O_3$ | $\mu$g/g | 34 ± 3 | 41 ± 4 | 44 ± 13 | 21 ± 2 |
| Se | $\mu$g/g | 0.076 ± 0.007 | 0.089 ± 0.004 | 0.073 ± 0.007 | 0.06 ± 0.005 |
| Br | $\mu$g/g | 2.86 ± 0.52 | 1.74 ± 0.07 | 0.18 ± 0.06 | 0.12 ± 0 |
| $Rb_2O$ | $\mu$g/g | 104 ± 3 | 132 ± 8 | 225 ± 45 | 30 ± 8 |
| SrO | $\mu$g/g | 54 ± 3 | 80 ± 2 | 84 ± 27 | 32 ± 5 |
| Y | $\mu$g/g | 23.6 ± 1.5 | 25.7 ± 1.6 | 17.7 ± 1.1 | 0.7 ± 0 |
| $ZrO_2$ | $\mu$g/g | 480 ± 22 | 384 ± 9 | 205 ± 13 | 16 ± 5 |
| BaO | $\mu$g/g | 362 ± 19 | 435 ± 16 | 899 ± 88 | 168 ± 57 |
| $WO_3$ | $\mu$g/g | 2.7 ± 0.3 | 2.9 ± 0.2 | 2.5 ± 0.8 | 0.9 ± 0.1 |
| Hg | $\mu$g/g | 218 ± 13 | 204 ± 14 | 201 ± 2 | 212 ± 15 |
| Tl | $\mu$g/g | 2.4 ± 0.1 | 2.3 ± 0.1 | 2.6 ± 0.5 | 1.5 ± 0.1 |
| Pb | $\mu$g/g | 25 ± 3.1 | 25.3 ± 0.9 | 28.8 ± 8 | 8 ± 3.5 |
| Bi | $\mu$g/g | 1.58 ± 0.12 | 1.78 ± 0.07 | 1.66 ± 0.1 | 0.97 ± 0.02 |
| Th | $\mu$g/g | 129 ± 14 | 130 ± 4 | 186 ± 18 | 9 ± 0 |

the soil profile is largely intact and at the elevation of the off-mound soil surface. This is substantiated by the fact that the depth of the gravel layer in the mound is correlated with the height of the mound above the surrounding landscape. The sizes of the gravel were also comparable between the on- and the off-mound sites. The proportion of gravel in the smaller mound profile above the concentrated gravel layer was less than 5% of the total amount of gravel in the profile (Figure 3). Thus, although there was some gravel in the mound above the gravel layer, this was a small proportion of the total amount. There was evidence at the study site of significant fossorial activity (rodent, porcupine and aardvark) on the mounds, making it likely that fauna redistributed some of the gravel upwards within the profile of the mounds.

A previous analysis by Cox et al.[2] of the small-sized stone content of *heuweltjies* supported the role of termites and fossorial animals. Because fewer stones were observed on- than off-mound, this led to the erroneous conclusion that bioturbation had led to the sinking of stones through the soil profile. However, these authors noted the limitation of their study and study site; the study mainly focused on surface layers (0–0.15 m depth), it took place in some *heuweltjies* where the concretionary calcrete layer prevented excavation beyond 0.3–0.4 m and these authors did not separate concretionary calcrete rocks from non-concretionary rocks. Furthermore, these authors did not consider that the lack of stones in surface layers may also be the result of aeolian deposition, rather than only being because of bioturbation. Our study site had the advantage of the continuous ancient gravel layer over a duripan, providing an indication of the previous soil surface.

Similar to previous reports,[7,13] there were differences between particles sizes on- and off-mounds. Movement of sediments by wind depends on the sizes of the sediment particles and the power of the wind.[25] Based on a compilation of studies of dust, Lawrence et al.[26] concluded that local dust deposition consists predominantly of coarse silts and/or fine sands, with 10–60% (by mass) of the particles being smaller than $20 \mu m$. Local dust generally also contains large fractions of fine silt (25–60%) and clay (10–40%). Regional dust, on the other hand, consists of less coarse silt and fine sands and a larger proportion of fine silt, but it has a clay content similar to local (within the same geological context) deposition. The particle size analysis reported here with greater concentrations of fine particles on-mound is thus consistent with a local source of sediment, as detailed by Lawrence et al.[26] In contrast, McAuliffe et al.[7] speculated that sediment at their site was derived from the coast and/or nearby dune fields. The local origin of sediments at our site is substantiated by elemental analysis, which showed that both on- and off-mound soils were strongly correlated with the elemental composition of shale rock sampled upslope from the mounds. McAuliffe et al.[7] concluded that sediments at their sites were well sorted. In contrast, the sediment sampled in this study was classified as poorly sorted. This could be the result of the better resolution provided by the laser diffraction particle size analysis compared to the hydrometer method. The occurrence of greater amounts of silt on- than off-mound is consistent with preferential aeolian deposition to the mounds, but accompanied by preferential loss of silt from the off-mound area and formation of a physical crust with vesicular porosity in places because of the wetting and drying cycles of fluvial action.[27]

Strong differences in elemental concentrations between on- and off-mound soils have been noted previously[13,14] and are generally regarded as the consequence of biotically (i.e. termite) induced accumulation of elements on-mound. It is possible, however, that off-mound elemental concentrations may be lower than those on-mound because of greater leaching of off-mound soils as a result of greater drainage through these lower elevation areas. The fact that concentrations of the relatively immobile elements Zr and Ti in off-mound soils are above the 95% confidence band of the correlation between off-mound soil and shale and that the slope of the line is less than 1 indicates that leaching of other more mobile elements has indeed occurred. Despite this general trend, some elements (notably Ca and Mn) have accumulated relative to other elements in mound soils, as the concentrations lie above the 95% confidence band for the correlation between on-mound soils and shale. The fact that Br is high in both on- and off-mound soils relative to shale

is surprising, but may indicate some marine influence.[28,29] Strontium isotopes and $\delta^{13}C$ values in *heuweltjie* calcrete at Clanwilliam were not similar to that in surrounding geology, leading to the suggestion that they may be of marine origin.[12] Interception of atmospheric nutrients by vegetation is not unusual[30] and thus, in addition to vegetation trapping aeolian sediment to form the mound and concentrating nutrients, plants may additionally intercept nutrient particulates and aerosols, consequently enriching the soil over prolonged periods.

This site appears to have much in common with the inland mounds studied by McAuliffe et al.[7] Similar to their Soebatsfontein mounds, the mounds in this study showed great diversity in the development of calcic horizons. The biggest mound surveyed had a well-developed calcrete layer (0.95 m) in combination with a reddened (5YR) argillic duripan layer. This calcrete layer appears to have formed in gravelly materials.[31] The smaller mound profiled (Figure 3) was only moderately calcareous at a depth of between 0.2 m and 0.4 m (7.5YR 5/6), but no distinct structural or textural differentiation at this level, and no significant petrocalcic horizons were present in the mound. McAuliffe et al[7] highlight the fact that the presence or absence of calcic horizons could be the result of significant age or developmental differences between the mounds because of the time-dependence of the formation of such horizons. The two mounds profiled here are in very different positions in the landscape, which could also contribute to significant developmental differences in the mounds. Furthermore, the horizons above the calcrete on the larger mound were softer, less-cohesive and easier to sample than those of the smaller mound, contrary to what one might expect based on the presence of the well-developed calcic horizon. This could imply younger sediments accumulated on an older, previously existing surface. In addition, McAuliffe et al.[7] also identified a 'strongly indurated, silica-cemented duripan' in the off-mound areas at 0.3 m depth. A similar reddened, cemented duripan was present on- and off-mound in the present study area, in conjunction with and just below a concentrated gravel layer. The horizons above this layer on-mound contain similar fine-textured sediments throughout the mound with limited pedogenic alteration, which combined with the lack of gravel supports the role of aeolian deposition.

Of the elements analysed (Figure 7), only Na and Zr were at significantly higher concentrations off- than on-mound (Figure 6). While Na is relatively mobile in soils and could be readily leached from the lower elevation off-mound soils, Zr is considered relatively immobile[34] and is likely to be higher in the off-mound soils because of loss of other elements associated with finer soil fractions. The on-mound accumulation P, K, Ca, Fe, Al and Rb and higher pH relative to off-mound sites may also be associated with the greater silt content of the mound soils, because like these finer particle sizes, these elements increased in concentration with depth through the mound profile. This indicates that there is a degree of pedogenic development within the mounds, substantiating the antiquity of the mounds. The significant increase in P concentration with elevation above the duripan may indicate plant depletion of this regionally scarce resource,[35] particularly from deeper and older horizons within the mound.

The results presented are consistent with aeolian deposition occurring preferentially on mounds as a result of increased surface roughness and sediment trapping provided by vegetation clumps. Alternatively, regional aeolian sediments deposited over a gravel plain might subsequently have been eroded, leaving mounds associated with vegetation clumps that reduce erosion. McAuliffe et al.[7] argued that the absence of pedogenically advanced layers on-mound ruled out the erosion hypothesis, because, if these sediments were part of a much older surface, the on-mound horizons should have undergone substantially more pedogenesis than is evident. Furthermore, for most sites where *heuweltjies* occur there is no evidence of extensive mantling by aeolian sediment, apart from that associated with the mounds. The mounds thus differ from the surroundings by having less pedogenically developed soil and distinct vegetation. Based on texture and elemental analysis, the sediment at our study site and that at the site studied by McAuliffe et al[7] is of local origin, making it unlikely that it was part of a regional mantling by aeolian sediment.

Although a predominantly erosional hypothesis seems unlikely, fluvial erosion of sediments and channelling of water between mounds is potentially an important process maintaining the sediment and profile differences between on- and off-mound areas. McAuliffe et al.[7] previously noted differences in pedogenic development between surface layers on- and off-mounds and suggested that this reflected the longer period that off-mound soils have had to develop. Our analysis suggests that the buried surface within mounds and associated duripan development does not differ strongly with that off-mound. The existence of physical crust with vesicular porosity and drainage lines at our study site, however, indicates the important contribution of fluvial processes to mound formation, and particularly the off-mound soils. Comparing the *heuweltjie* landscape morphology to analogous modern landforms and processes, like drainage patterns and nebkhas, provides clues to the processes that shaped them. Seifert et al.[8] concluded that the mounds they studied in Arkansas are relict nebkha dunes even though the centimetre-resolution profile of one of the mounds revealed only a slight asymmetry. The absence of features associated exclusively with water erosion, such as distinct terrace structures, potentially precludes an exclusively water erosion hypothesis, especially taking into consideration the moderate slope at the current site. Unlike for mima-mounds in North America,[32] there has never been a suggestion that *heuweltjies* from different parts of South Africa[33] are polygenetic in origin. It is possible, however, that contributory deposition and erosion processes act to different degrees and have site-specific outcomes for pedogenesis. For example, it has been suggested that nebkhas are strongly influenced by local factors such as sediment supply, local climatic conditions, plant density and growth rates and the interaction between these various factors.[36]

## Conclusion

We concur with McAuliffe et al.[7] that *heuweltjies* are predominantly the consequence of aeolian deposition, probably around vegetation clumps. We question the role of termites in the formation of the mounds or their chemical composition. The physical and chemical properties of mounds are consistent with locally derived aeolian sediment deposition, but with some exotic sources of elements such as possibly marine derived Ca and Br delivered via atmospheric transport. We agree that globally, the origins of large earthen mounds are probably polygenetic[32], and that in other areas, such as the campos de murundus of Brazil[6] and the mima mounds of Washington State[37], these may well be primarily formed by erosion, rather than deposition.

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## Authors' contributions

All authors participated in conceptualisation and field sampling. M.D.C. and J.v.H. analysed data and wrote the manuscript. J.J.M. and L.K. edited the manuscript.

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